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HV ON-SITE TESTING ON CABLES BY ALTERNATING VOLTAGE OF VARIABLE FREQUENCY

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Frequency-tuned resonant test systems are, meanwhile, state-of-the-art for on-site testing and diagnostics on high-voltage plastic-insulated cables.

The paper describes the basic idea and relations of this particular type of test systems. After experience with several commissioned systems, the technical data, especially the specific weight and the performance have been further optimised. A specially adapted diagnostic technique has been developed for the application together with test systems of variable frequency. Basic research on cable samples with different failures has obviously qualified AC voltage near to the power frequency to be the optimum test voltage wave shape. Resulting from these it is logical to apply this test voltage shape also on medium-voltage cable systems. An example is also introduced in this paper.

The latest international standard issues in this field consider already the described testing method.

1. PRINCIPLE FOR HV TESTS ON-SITE

A general principle of the insulation co-ordination and HV testing is that the applied test voltage simulates the stress which can occur during the operation of the HV apparatus test. High voltage tests should provide the information for the decision whether a defect in the insulation is dangerous or not for the later operation. That means the failure mechanism (caused by the kind of defect and the kind of the voltage stress) during the HV test and the later operation should follow the same physical process. To accelerate this process, the test voltage is usually higher than the corresponding stress during operation.

This acknowledged principle for HV testing in the test laboratories of a factory cannot be easily transferred to HV on-site test. Main restriction is the availability of the HV test system on site.

Furthermore a HV on-site test is executed on equipment, which has been type and routine tested in the factory. It only needs to be demonstrate that there are no critical defects caused by transportation or on-site assembling.

The most important stress of a XLPE cable in service is the stress with the operational alternating voltage. Consequently the most favoured on-site test voltage should be an AC voltage of power frequency, standardised for laboratory testing in the range from 45 to 65 Hz. But for on-site testing a larger frequency tolerance is being discussed. If an on-site test is completed with a partial discharge (PD) measurement, all the experience from the various factory tests can be transferred to the on-site test then.

2. GENERATION OF AC TEST VOLTAGE ON-SITE

In general **AC** test voltages can be generated with one of the following systems (Very Low Frequency (VLF) test systems with test frequencies less the 1 Hz are not considered):

ACTC = conventional test **T**ransformers with **C**ompensating reactors (mainly on the low-voltage side) of power frequency (Fig. 1a),

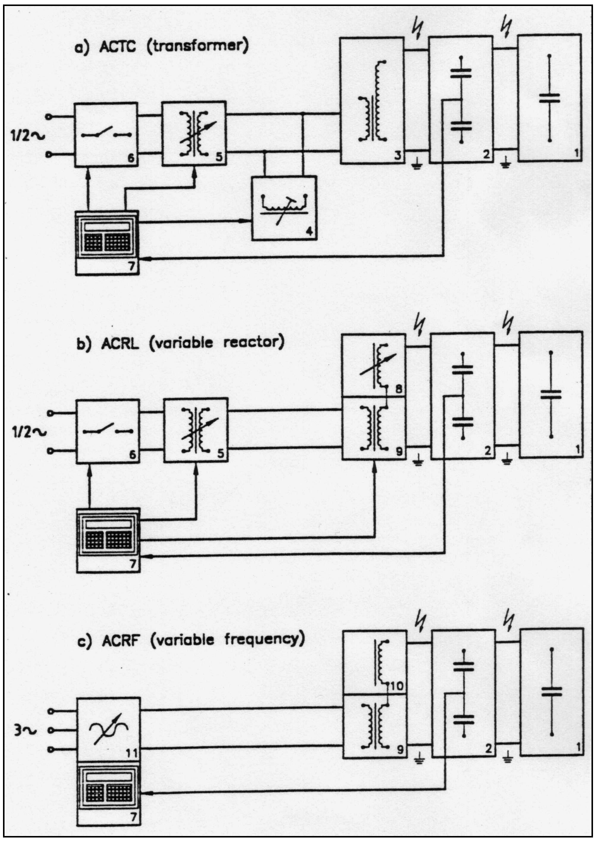

Fig. 1. Circuits for AC test voltage generation (simplified): 1– test object, 2 – voltage divider/coupling capacitor, 3 – test transformer, 4 – compensating reactor, 5 – regulating transformer, 6 – switchgear, 7 – control and measuring unit, 8 – tuneable reactor, 9 – exciter transformer, 10 – fixed reactor

ACRL = **R**esonant circuits based on tuneable HV reactors (inductance) at the power frequency (Fig. 1b),

ACRF = **R**esonant circuit based on HV reactors with fixed inductance tuned into resonance by variable **F**requency supplied by a frequency converter (Fig. 1c).

ACTC and ACRL test systems are well introduced for factory testing. However ACRF test systems can be designed more compact than the traditional solutions. It is underlined by the comparison in Table 1, showing that high quality factors can be reached. Leading to extremely low specific weights.

Table 1. Comparison of circuits for AC test voltage generation on site

	transformer circuit **ACTC**	tuneable reactor circuit **ACRL**	tuneable frequency circuit **ACRF**
frequency	industrial frequency 50 or 60 Hz	industrial frequency 50 or 60 Hz	load depending frequency, selectable in the range of 20 to 300 Hz
quality factor $q = \frac{P_{test}}{P_{mains}}$	(up to 5) by compensation reactors	40 ... 60	60 ... 200
power supply	single phase or two phases	single phase or two phases	three phases
specific weight: system weight/ test power	15 to 20 kg/kVA	3 to 10 kg/kVA	0.5 to 2 kg/kVA
	Total weight and volume are in close relation to the specific weight		
max. equivalent 50 Hz test power	up to 500 kVA	up to 4 MVA	up to 35 MVA
number of power components	5	4	3
Mechanic characteristics	moving parts in the regulator	moving parts in the regulator and in the tuneable reactor	no moving parts, very compact design

The certain disadvantage of the load depending frequency is more than compensated by the compact design and low specific weight of ACRF systems.

An ACRF system (Fig. 1c) consists of the following components:

The **control and feeding unit** (7) is arranged in a cubicle and contains the power switch, the power frequency-converter (5) generating a square-wave voltage (20 to 300 Hz), and all control and measuring modules (6). The **exciter transformer** (4) adapts the square-wave voltage to the HV oscillating circuit, consisting of the **test object** (1), the **voltage divider** (basic load (2)) and the main component, the **HV reactor** (3). For the required high test currents the HV reactor is designed in a conventional tank-type design with oil-paper insulation and natural oil cooling. The used multi-gap core essentially contributes to the high quality factor of an ACRF circuit (Table 1).

3. CHARACTERISTICS OF ACRF TEST SYSTEMS

Resonance is achieved by tuning the frequency of the converter unit to the natural frequency (f) of the oscillating circuit formed by the reactor (L) and the cable under test (C). The test voltage is pure sine-shaped in the case of a series resonant circuit. Its frequency depends on the load capacitance according to the equation:

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

The frequency increases by decreasing the load capacitance (Fig. 2). The test current and the (reactive) test power are given by

$$I = V\sqrt{\frac{C}{L}} \tag{2}$$

$$P = V^2\sqrt{\frac{C}{L}} \tag{3}$$

with V = test voltage.

For a constant inductance L, is the minimum resonant frequency f_{min} is at the maximum load capacitance C_{max}.

In addition to the test voltage V, the maximum load capacitance C_{max} and the acceptable frequency range f_{min} to f_{max} is a decisive design criteria for the fixed HV reactor of the ACRF test system:

$$L = \frac{1}{(2\pi f_{min})^2 C_{max}} \tag{4}$$

$$I_{max} = V 2\pi f_{min} C_{max} \tag{5}$$

$$P_{max} = V^2 2\pi f_{min} C_{max} \tag{6}$$

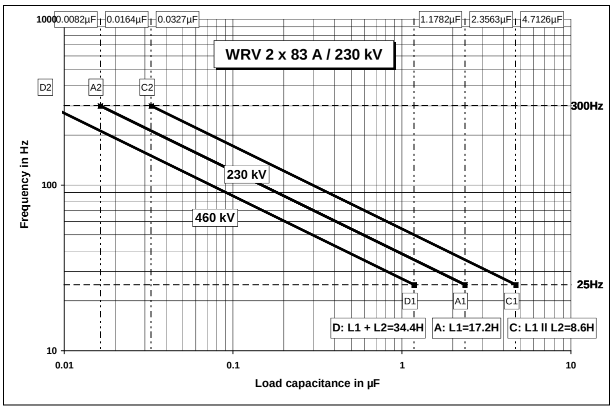

Fig. 2. Load diagram of an ACRF system (A: single test system, C: parallel connection of two systems, D: series connection of two systems)

The maximum reactive test power P_{max} decreases with decreasing f_{min}, and this would lead to lower size and weight of the reactor if not a certain counteracting tendency of the necessary cross-section of the magnetic HV reactor core would have to be considered.

The new draft of IEC 62067 /3/ recommends a frequency range from 20 to 300 Hz, corresponding to

$$\alpha = \frac{f_{\max}}{f_{\min}} = 15. \tag{7}$$

The relation between maximum and minimum load is according to equation (4)

$$\frac{C_{\max}}{C_{\min}} = \left(\frac{f_{\max}}{f_{\min}}\right)^2 = \alpha^2 = 225 \tag{8}$$

and characterizes the very wide range of testable cable lengths.

The quality factor (q) of a resonant test system is the ratio between test power P and required feeding power P_s

$$q = \frac{P_T}{P_S} \tag{9}$$

with P_S covering all ohmic losses in the test circuit. Because the polyethylene insulation of an extruded cable has a very low tan δ (about $3 \cdot 10^{-4}$), the quality factor is mainly determined by the resonant reactor and exciter transformer losses. A maximum quality factor is desirable regarding a minimum feeding power, but it would require large cross sections of the iron core and of the copper winding wire, resulting in a higher specific weight. For low frequencies (and therefore high currents) the quality factor is determined mainly by the pure ohmic losses in the copper wire, for higher frequencies by all frequency-depending supplementary losses. That results in a maximum of the quality factor over frequency. Figure 3 shows the quality factor and current versus frequency for a resonant test system.

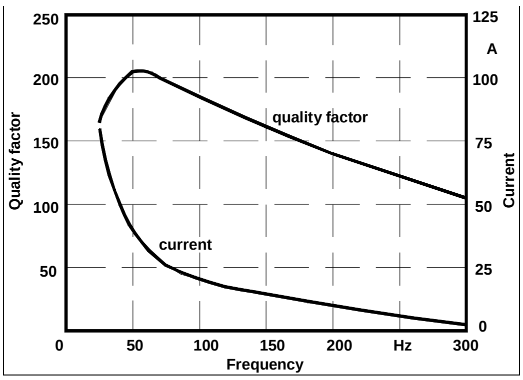

Fig. 3. Quality factor and current vs. frequency of a resonant test system 80 A, 254 kV

The quality factor of around and better than 160 reduces with the specific weight of the testing system to 0.8 kg/kVA only.

Both effects, the lowering of the test power by a lower frequency and a sufficiently high quality factor, which is much higher than for resonant reactors with variable inductance, enable the generation of some 10 MVA test power by an on-site available feeding power of some 100 kVA.

4. EXPERIENCE WITH AFCRF SYSTEMS

4.1. RANGE OF MANUFACTURED SYSTEMS

Systems manufactured until now apply different minimum frequencies (f_{min} = 20 ... 36 Hz) according to the special request of the customers. Therefore and with reference to the power frequency, the 50 Hz equivalent power

$$P_{50} = \frac{50}{f_{nin}} * P_T \tag{10}$$

is introduced. Figure 4 shows the extremely high power demand for on-site cable tests. On-site cable tests can demand an extremely high testing power (Fig. 4: cable lengths; testing voltage and required power). The dots mark commissioned ACRF test systems ● single test systems; ▲ series or parallel combination; □ largest quoted systems). The largest quoted systems (open marks). It demonstrates that the majority of HV XLPE cable systems installed on-site can be tested with the presently available test systems under taking into consideration the series or parallel operation of two systems.

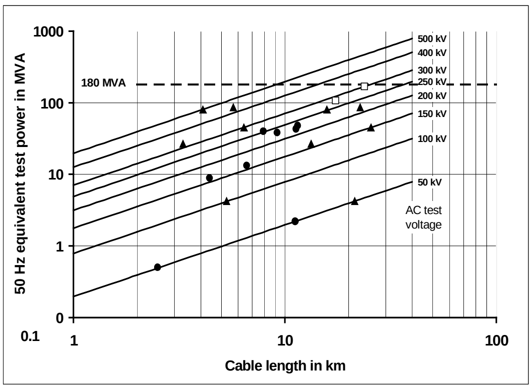

Fig. 4. 50 Hz equivalent test power and realized ACRF test systems

4.2. TRANSPORTATION SYSTEM

In spite of modern cable on-site test systems lowest specific weight, the resulting total weight of such a system is about 30 tons.

The systems can be installed on truck trailers being modified for this purpose (Fig. 5 shows a typical trailer). The control and feeding unit including the inverter is located in an air-conditioned and illuminated 10 ft container at the front side of the trailer. It serves for the operation of the system. The resonant reactor is located above the trailer axles, its bushing points to the rear side. The exciter transformer is standing between the container and the resonant reactor. The trailer has a foldable roof and side canvas to protect the system during transport and parking.

Alternatively, under consideration to future ship transportation all control equipment and the exciter transformer can be arranged in a 20 ft container. The resonant reactor is designed to fit on a flat rack container. For its fixing, it has counterparts for container twist locks at the bottom plate and for lifting container fittings at the top plate.

4.3. CONNECTION TECHNOLOGY AND ACCESSORIES

Sometimes it is impossible to install and operate the test system in the immediate vicinity of the cable to be tested. So it is necessary to lead the test voltage over a short distance. That can be done by a bar wire supported by insulating posts. Thereby the entire transmission line must be protected by a safety loop with warning lamps and emergency-off switches. A more convenient solution is to use a connection cable with two flexible bushings at the ends – one is connected to the HV terminal of the resonant reactor and the other one to the cable to be tested. By means of this cable the test voltage can be lead easily into indoor substations or down to underground cable facilities. Tank-type resonant reactors enable also the direct plug-in connection of such connection cables.

4.4. SOFTWARE FOR CONTROL AND TEST REPORTS

The control and feeding unit contains all power electronics and control modules required for operating a frequency-tuned resonant test system. The entire system is controlled by a PLC, type SIMATIC S5-95U. An operator panel COROS OP 17 is used for the input of the test data and to display the measured values (voltage, frequency, current) and other necessary information about the state of the system. For a remote control, the SIMATIC unit can be linked to an external PC, preferably a laptop, via an RS 232 interface. The computer with a special software enables a more comfortable operation of the system. This software records all relevant data like test voltage, test current, frequency, inverter pulse width, resonant reactor temperature etc. on the hard disk. After the test, a complete test record can be generated based on these dates.

4.5. DIAGNOSTICS TECHNIQUE

Frequency-tuned resonant test systems can be prepared for PD measurements according to IEC 60270. For the suppression of disturbances caused by the steep switching transients of the inverter bridge the control and feeding unit generates a signal to trigger the gating unit of an specially modified PD detector. Additionally HV filters consisting of measuring capacitor, blocking impedance and coupling capacitor can be applied for PD measurement purposes (see Fig. 5 right side). A PD sensitivity below 10 pC has been measured. Obtainable PD sensitivity under on-site conditions depends on the electromagnetic environmental conditions and on the damping conditions and length of the cable. It is estimated that the IEC 60270 method can be applied up to a cable length of max. 2.5 km, when the PD measurement is executed only from one end, and max. 5 km from both ends. The sensitivity becomes too low for longer cables and non-conventional methods must be applied.

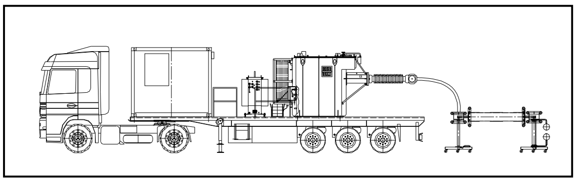

Fig. 5. Frequency-tuned resonant test system 90 A, 150 kV on a trailer with HV filter for PD measurement

5. FREQUENCY-TUNED RESONANT TEST SYSTEMS FOR MEDIUM-VOLTAGE (MV) CABLE TESTING

After frequency-tuned resonant test systems have been successfully introduced for the on-site testing of HV cables, there is a certain logic to apply the same principle also to testing of MV cables. Especially from the point of view to enable PD and tan δ diagnostics. Different to HV extruded cables, a worse tan δ has to be considered for MV cables, thus effecting the quality factor of the resonant circuit. It is not necessary to design exciter transformer and resonant reactor for an extremely high quality factor. This is also possible, because a much lower feeding power related to HV cable test systems must be supplied. The resonant reactor (Fig. 6) is made in a conventional power transformer design, i.e. oil-immersed in a metal tank.

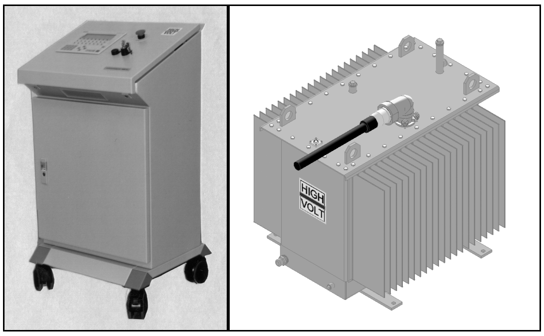

Fig. 6. Control and feeding unit and resonant reactor 17 A, 36 kV for testing cables up to 10 km

It contains the active part (coil and core) and a capacitor for the voltage measurement. The test voltage is lead out via a plug-in connection and a 20 m-connection cable with a air cable termination at the other end. The control and feeding unit is connected to the resonant circuit via a dry-type exciter transformer. The desk type control and feeding unit contains all power electronics and control components including a peakvoltmeter.

6. CONCLUSIONS

Remarkable progress has been made in the design and performance of frequency-tuned resonant test systems for on-site testing and diagnostics of HV extruded cables:

A frequency range from 20 Hz to 300 Hz reduces the specific weight of such test systems to 0.8 kg/kVA or lower.

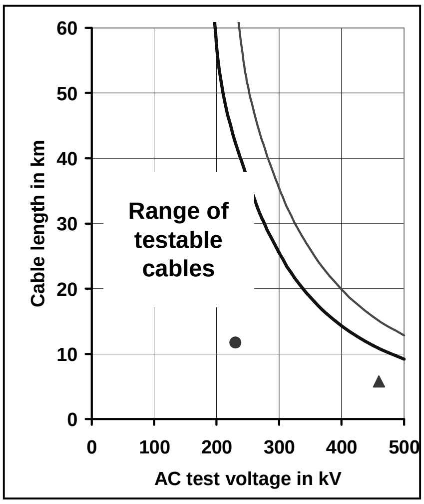

Fig. 7. Testable cable length and AC test voltage, based on max. test power 180 MVA (250 MVA in future)

A tank-type reactor with radiators is the optimum solution related to the permissible duty cycle and a plug-in connection technology to the cable under test.

There are optimised solutions for the transportation of such test system based on containers and trailers.

An adapted PD technique and comfortable PC software for control and protocol are available.

The application of frequency-tuned resonant test systems for the on-site testing of medium-voltage cables is a logic conclusion.

For the range of HV, UHV (EHV) cable systems Fig. 7 delivers an impression, which cable lengths at which voltages can be tested with available ACRF test systems.

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